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First Quarterly Report, ~~On~~

An Investigation Of

Fluid Extrusion Of Metals

July 2, 1963 - Sept~~ember~~ 30, 1963

[2] (NASA Contract NASw-742)

to

Alfred Bobrowsky Sept. 30, 1963 refs

National Aeronautics and Space Administration
Washington, D. C.

[redacted] by

Pressure Technology Corp~~oration~~ of America
453 Amboy Avenue
Woodbridge, ~~New Jersey~~

PRESSURE TECHNOLOGY CORPORATION OF AMERICA
453 Amboy Avenue
Woodbridge, New Jersey

October 1, 1963

Gentlemen:

Please find enclosed one copy of the First Quarterly Report entitled "An Investigation of Fluid Extrusion of Metals", produced under Contract No. NASw-742, for the National Aeronautics and Space Administration.

Yours very truly,

Alfred Bobrowsky

Alfred Bobrowsky
President

AB:mw

Enclosure

September 30, 1963

First Quarterly Report On An Investigation Of Fluid Extrusion Of Metals

July 2, 1963 - September 30, 1963

Contract NASw-742

to

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453 Amboy Avenue
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ABSTRACT 16601

Tensile tests under pressure have begun on NASA Nickel-Base Alloy TAZ-8.

Fluid-to-fluid extrusions have been conducted successfully on series 300 Mar-Aging steels, both annealed and hardened.

Several lubricants have been evaluated in the fluid-to-fluid extrusion of steel. Excellent finishes can be produced.

AUTHOR

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INTRODUCTION

I. General

The usual types of extrusion and extrusion equipment are well-detailed in reference 1 for both hot and cold operation. All are characterized by the relative motion of a billet through a die or over a mandral by the force of a solid ram.

Bridgman (reference 2) described attempts at extrusion with the conventional ram replaced by fluid pressure. He found that greater reductions in area were possible with the fluid technique compared to the ram method. Unfortunately, he also found that yet larger reductions in area resulted in "spitting out of the metal in gulps".

In the fluid-extrusion process, the billet does not contact the chamber wall. Consequently, Bridgman reasoned, the friction of the billet on the chamber wall usual during the ram-type extrusion would not be present with the fluid-type extrusion. This friction force with the ram may be so great as to prevent the extrusion of long billets--if ram force is increased the chamber wall may rupture under the pressure.

Bridgman concluded that the fluid-extrusion method might offer possibilities if greater reductions of area were effected.

Most recently, several experimenters have used fluid pressure in one or more ways in the extrusion process, with often surprising results.

British research in the field of fluid-pressure extrusion has been of two types:

a) Ram extrusion into a high-pressure chamber (references 3a, 4, and 5), and

b) Fluid-pressure extrusion into atmospheric pressure (references 3b, 4, and 5).

Ram extrusion into a high-pressure chamber revealed that metals that are difficult to extrude by conventional means could be handled by this technique. Magnesium was extruded with a reduction in area of 66%, and exhibited excellent finish. It is noted that surface finish was better at lower fluid pressures (17,600 p.s.i.) than at higher (128,000 p.s.i.).

Bismuth was also extruded (reduction in area of 56%) without difficulty, with good surface finish at pressures of 20,000 p.s.i. It was believed that this technique offers two advantages:

i) Extruded shapes can be produced of materials not previously extrudable, and

ii) Heat treatment after cold plastic deformation of brittle materials could lead to a refined grain size thereby endowing the metal with some ductility.

It is noted that tubes were extruded by this method also. A 60/40 brass that ram-extruded as tiny pieces was extruded as a tube (74% area reduction) in one piece, although cracked.

As fluid pressure increased, there was a tendency for the microstructure of the extruded product to decrease the amount of twinning.

Fluid-pressure extrusion into atmospheric pressure revealed:

a) Wall friction is eliminated, reducing extrusion pressures;

b) Small die angles can be used, reducing extrusion pressures;

c) Long billets can be extruded
   i) because of reduced friction, and
   ii) because of continuous lubrication of the die;

d) Since the fluid pressure supports the exterior of the die, thinner die walls can be used;

e) Physical properties are more uniform across the cross-section of the extruded material.

Soviet research (reference 6) has been along similar lines except that this group added fluid-extrusion into a pressurized chamber as a third method, disclosed during 1959. Some results of fluid-pressure extrusion were:

a) Preliminary tensile tests under fluid pressure yielded 67% reduction in area for a steel specimen of Rockwell C-60;

b) There were successfully cold-extruded steels, copper, and aluminum alloys;

c) Reverse extrusion can be done by fluid-pressure methods;

d) The differential pressure to fluid-extrude aluminum into a pressurized region is independent of pressure level;

e) Different fluids produce different finishes and require different extrusion pressures;

f) The extruded metal carries a thin fluid layer through the die for continuous lubrication;

g) Die wear is greatly reduced; and

h) Hardness across the cross-section of fluid-extruded metals was very uniform, in contrast with that for ram extrusions.

The Soviet apparatus is described in reference 7, and is similar to its British and American counterparts except for additional features contributing to ease of operation. It too could be used to extrude tubing, as well as profiled shapes.

The extremely large reductions possible by fluid extrusion are not usually achievable in any other way. Reductions of over 90% are repeatedly achieved. For example, reference 8 tells of a 90% reduction obtained with a 0.7% Fe + Si + Cu aluminum alloy with a fluid pressure of 67,000 p.s.i. Reference 9 mentions a .07%-carbon iron with 98% reduction by multiple passes, resulting in ultimate tensile strength of about 140,000 p.s.i. although only with about 1% elongation in a gage length of 10 diameters (compared to usual 4-diameter gage lengths).

The best explanation for the combination of results thus obtained appears to be that the hydrostatic-pressure environment provides certain ductility benefits not present in ram-type extrusion. The entire process is essentially deformation of a solid by shear while under pressure.

This program is concerned with:

a) The suitability of fluid-to-fluid extrusion for several materials, and

b) The properties of materials that have been successfully fluid-to-fluid extruded.

II. Technical

A. Preliminary

The stresses on a solid may be classified as direct (normal) and shear. If three mutually orthogonal planes are chosen on which shear is zero (which can always be done), the resulting normal stresses are the principal stresses, s_1 , s_2 , and s_3 . The average of these principal stresses is the hydrostatic component of stress, s , compression taken as positive.

$$s = (s_1 + s_2 + s_3)/3$$

The principal-stresses-less-s are the principal-stress deviators,

$$s_1' = s_1 - s; \quad s_2' = s_2 - s;$$
$$s_3' = s_3 - s.$$

The second deviatoric stress invariant, J_2' may be given as

$$J_2' = (s_1' \ + s_2' \ + s_3' \ ).$$

J_2' is frequently used as a criterion for plastic flow. Its value is found at the onset of yield in a uniaxial (usually tensile) test, say J_2' (crit). Whenever J ' in a multiaxial condition exceeds the value J_2' (crit), theory states that plastic flow will occur (reference 10).

1

2

B. Brittleness and Ductility

Brittleness is characterized by lack of permanent deformation after fracture in a mechanical test, or at most very little deformation. Ductility (plasticity) connotes appreciable permanent deformation conversely.

Along with Nadai (reference 4, page 58), this report does not describe materials as either brittle or ductile, but speaks of the "brittle state" or "ductile state" of a material. The reason for this usage is that a given material may be either in brittle state or ductile state according to its temperature, external pressure, and occasionally fluid environment.

A usual method of expressing amount of ductility is by percentage reduction in area at the neck of a tensile specimen. Also frequently used is the percentage elongation in a gage length four diameters long.

C. Brittle-Ductile Transition (BDT)

Nadai (reference 11, page 58) states,

> "Tests of materials carried out under high pressure show, however, that the so-called 'brittle' materials, without exception, may, under suitable mechanical conditions, be brought into the plastic state."

It is well-known that the change from brittleness to ductility can be brought about by an increase in temperature, frequently through a narrow range termed the transition temperature (reference 12, page 375).

Not so well known is the fact that an increase in pressure can also cause a change from brittle state to ductile state (reference 13, page 193). This effect can be very large (reference 4), as for zinc where a relatively small change in surrounding pressure changes percentage reduction in area from 8% to essentially 100% in a tensile test.

The change from brittle state to the plastic state due to increase of temperature and/or pressure is termed the brittle-ductile transition (BDT).

A further phenomenon of interest is that the BDT pressure is lower in compression than in tension (reference 13, page 225).

D. Effect of Pressure on Ductility

Bridgman (reference 2) has shown how increase of pressure can increase ductility in steel. Tensile tests of steel specimens under fluid pressures manifested larger reductions-in-area as the pressure increased. Punching tests on steel similarly showed that as the pressure of the fluid environment increased, the punched disc could be forced nearly through the entire sheet thickness without fracture.

Other investigators similarly have found for many materials that amount of deformation-without-fracture can be increased in compression and torsion tests when under pressure.

III. Analysis

When a solid under pressure, p , is subjected to uniaxial tension, s_1 , the average hydrostatic stress is

$$(3p_t - s_1)/3 = s_o$$

Similarly, in uniaxial compression, s_1 , the average hydrostatic stress is

$$(3p_c + s_1)/3 = s_o$$

Assuming the BDT pressure under pure shear to be $s_b = p_b$, it can be seen that

$$p_c < p_b < p_t \cdot$$

This relationship explains qualitatively the last paragraph in section IIC where experimentally it is found that $p_c < p_t$.

Actually, on substituting experimental values of yield stress under pressure (as from reference 5, pages 200-209), the observed variation of BDT pressure with sense of stress may be made quantitative.

The usual assumption in all plasticity theory is that J_2' is independent of pressure. It is noted that in the calculation indicated above, the actual values of yield points in tension and compression were not the same, exhibiting the basic inadequacy of the assumption of J_2' pressure-independence. Soviet literature tends to corroborate that J_2' should be regarded as a function of other variables such as average stress, at least, in some cases.

IV. Theory

The theory that, from many points of view, most adequately explains the phenomena described in the background portion of this report is a variation of the microcrack theory. It is not postulated that microcracks exist as such, but it is believed that crack-like defects -- having closely conforming surface, interior to a solid, that do not cohere -- may be present.

It is further postulated that hydrostatic pressure alone does not affect these cracks, but that the combination of shear and pressure can heal cracks and/or suppress their propagation (in the absence of excessive stress gradients).

For example, the failure of a tensile specimen begins with an internal crack in the region of highest shear (the neck) of the specimen. If ductility is to increase with pressure, this incipient crack must be healed by the shear-cum-pressure. It was noted that ductility does increase with pressure, lending credence to the healed-crack theory.

It has been noted in many places (reference 14) that cold work frequently results in an increase in microcracks (not dislocations). The BDT appears to be an example of crack suppression on this basis.

Results of microscopic shear generated in the austenite-martensite transformation under pressure (by rolling at cryogenic temperatures of types 301 and 302 stainless steels) support this view.

The results of punching under pressure mentioned earlier are directly explainable by the crack-healing theory.

It is believed that direct experimental evidence to substantiate or to contradict this theory should be sought. This, however, is not the primary subject of this report.

This theory has been mentioned here to explain some results of the fluid-extrusion process.

V. Experimental

Fluid pressure can be used in extrusion in three ways:

a) ram extrusion into a region of high fluid pressure,

b) fluid-pressure extrusion (replacing the ram) into atmospheric-pressure, and

c) fluid-pressure extrusion into a region of lower (yet considerable higher than atmospheric) pressure.

At this point, only c) will be considered, namely, fluid-pressure extrusion into a pressurized region.

If the preceeding theory has validity,

a) physical properties should be enhanced over ram extrusion,

b) brittle materials should be extrudable (or those with limited capacity for cold work), and

c) greater ductility of the work should mean greater reductions possible, perhaps at lowered pressure.

Preliminary results from references 3a and 3b support these inferences:

a) Bi and Mg difficult to extrude because of limited capacity for cold work, extrude easily and with good surface finish, into a pressurized region;

b) high reduction ratios (up to 96% for an aluminum alloy) were achieved; and

c) extrusion pressures were lowered.

Results from translated Russian sources corroborate these results:

a) Iron (.07% C) extruded with 98% reductions by several passes;

b) Strengths were improved for iron;

c) At 90% reduction, fluid-pressure extrusion required less pressure than used for ram extrusion, for a commercial-grade aluminum (with Fe, Si, and Cu).

Other results from abroad have indicated that physical properties are more uniform across the cross-section of fluid-extruded material than for ram-extruded material.

The general conclusion is that materials ordinarily thought to be difficult to cold work to an appreciable extent may in fact be extruded under pressure, and with good finish, large reductions, and in long lengths. Profiled shapes were successfully extruded also (reference 6), with some elementary precautions in die design.

EXPERIMENTAL

Tensile Tests Under Pressure

The tensile tests under pressure were performed in a manner somewhat similar to that of Bridgman in reference 2. The test specimens had dimensions shown in figure 1, about 0.160-inch diameter of test section, with a 1/2" gage length including fillets. Inasmuch as reduction-in-area and not unit elongation is of primary concern, the fact that the gage length is not the usual four diameters in length is of not major consequence.

The tensile specimens are placed in tensile fixtures such that compression of the fixture yields tensile force on the specimen. The same piston that compresses the pressurizing fluid also loads the tensile fixture. The tensile data are taken as piston displacement versus primary pressure. An elastic magnifier, load sensitive, increases sensitivity in the elastic range by a factor of 20:1. Load sensitivity is plus-or-minus 500 p.s.i., stress sensitivity is plus-or-minus 5000 p.s.i., and displacement sensitivity is 0.0005 inch in the plastic range, 0.00003 inch in the elastic range.

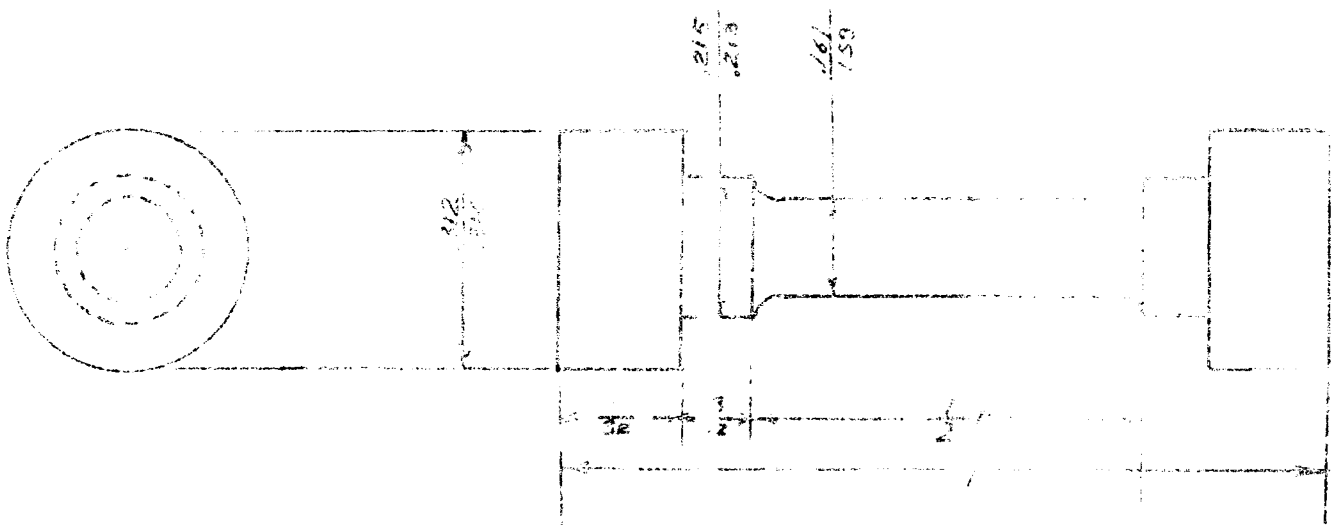


FIGURE 1 TENSILE SPECIMEN

ALL DIMENSIONS IN INCHES

The entire tensile apparatus is a standard Alpha-Press with tensile-test accessories, manufactured by Pressure Technology Corporation of America.

Fluid-to-Fluid Extrusion

Fluid-to-fluid extrusion is performed in a standard Beta-Press (fluid-to-fluid extrusion machine), manufactured by Pressure Technology Corporation of America. The principle of the process is shown in figure 2. A billet is extruded *by* fluid pressure *into* fluid pressure. The receiver pressure is termed p . The extrusion pressure is symbolized $(p + \Delta p + dp)$ where Δp is the pressure differential required to fluid-extrude the specific material into atmospheric pressure, and dp is a correction factor to account for changes (if any) in the differential pressure as the pressure level rises. The term Δp should be correlatable with J_2', the criterion for yield. The term dp should be a function of the hydrostatic component of stress, s .

Materials

Three materials have been studied to date. The first is a 300-series Mar-Aging steel of trade name Almar 18 (300),

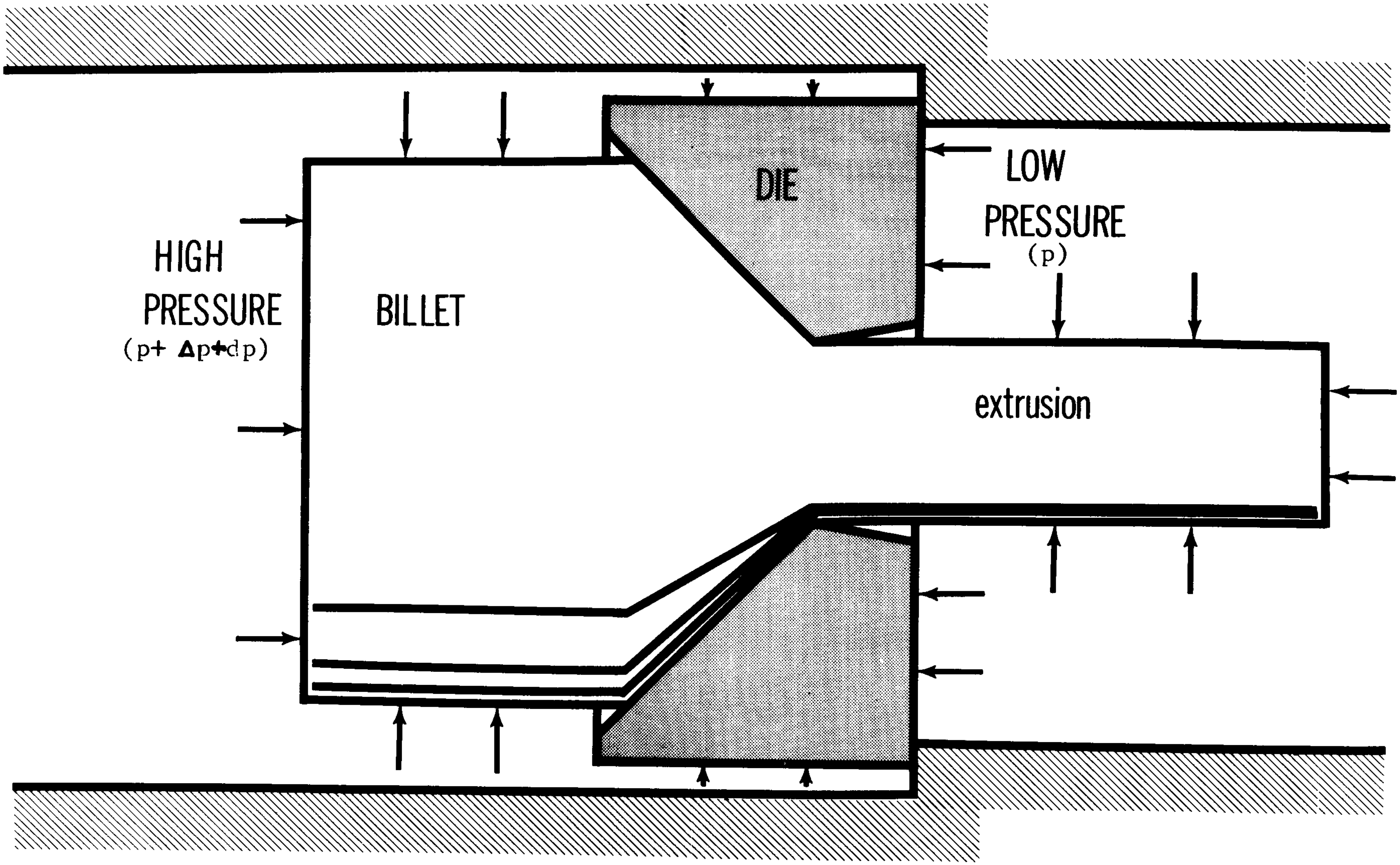


Figure 2 -- Schematic drawing of fluid-to-fluid extrusion process. Billet, die, and extrusion are completely within the pressure environment throughout the process.

kindly furnished by Dr. E. Reynolds of the Allegheny-Ludlum Steel Corporation. This material was examined briefly in the annealed and in the hardened condition. Billets were 0.250-inch in diameter, in lengths up to 1 inch. The physical properties of the billets, as determined from tensile specimens are as in table I.

Table I

Tensile Properties of Mar-Aging Steels

Condition	YS, KSI	UTS, KSI	RA, %
Annealed	127.5	157	71
Annealed	122.2	154	72
Hardened	-----	276	60
Hardened	274.5	278	56
Hardened	266	270.5	58
Hardened	273	276	57

The second material was an AISI 1015-1020 steel in the annealed condition. This material as 1/4 -inch diameter rod was used primarily for lubrication studies in fluid-to-fluid extrusion. It is believed that results for lubricants on this steel will be valid for any carbon steel or low-alloy steel. The yield point for this material was about 38,000 p.s.i.

The third material was NASA Nickel-Base Alloy TAZ-8 rod, as-cast, 1/2" in diameter, furnished by the sponsor. The nominal composition in weight percentages is:

.125	C
2.5	V
4.0	W
4.0	Mo
6.0	Cr
6.0	Al
8.0	Ta
1.0	Zr
Bal	Ni

Some preliminary data on this alloy are given in NASA TN D-1531 of April 1963 ("Continued Investigation of an Advanced-Temperature, Tantalum Modified, Nickel-Base Alloy", by J.C. Freche and W.J. Waters). The room-temperature properties of three specimens of the as-cast alloy were:

UTS, PSI	Elongation, %
133,700	1.2
126,400	9.5
143,500	4.8

RESULTS

Mar-Aging Steel

As preliminary investigation, four billets of hardened and two billets of annealed 300-series Mar-Aging steel were reduced by fluid-to-fluid extrusion. Both billets of annealed material were reduced 28%. Then one of these was further reduced 41% by partial extrusion for a cumulative reduction of 57%.

One hardened billet was reduced 28%. Another was reduced 29% and then partially fluid-to-fluid extruded another 40% for 57% cumulative reduction. An axial crack formed in this piece. Another billet was reduced 50% in a partial extrusion. The last billet was reduced successively 50% and 29% in partial extrusions for a cumulative reduction of 65%.

Although the annealed billets had the heat-treating scale removed as did all but one of the hardened billets, one hardened billet was fluid-to-fluid extruded with scale on. Some of the scale passed intact through the fluid-to-fluid extrusion process.

NASA Nickel-Base TAZ-8 Alloy

A single tensile specimen was pulled under 110,000 p.s.i. pressure. A yield point was not definitely discernible, but if present was the same as the UTS, about 124,000 p.s.i. Percentage reduction in area was 6, and percentage elongation in 1/2-inch was 8. The fracture was at one fillet at the end of the gage length, and may not be representative of the properties of this material.

AISI 1015-1020 Steel

A small study of lubrication characteristics of this steel in fluid-to-fluid extrusion was made. The results are shown in the figures 3-8 that follow. The extrusion pressures are given as a percentage of a nominal value, since they depend on die design, billet configuration, surface finish, and other variables. All reductions were at a 1.43:1 ratio except for an attempted 11.4:1 reduction using gasoline, that simply nosed the billet more. Table II tabulates some significant information on these tests, all in 40°-nosed billets except as noted.

Figure 3 -- Fluid-to-fluid extruded AISI 1015-1020 steel. Reduction ratio, lubricant, and relative extrusion pressure shown.

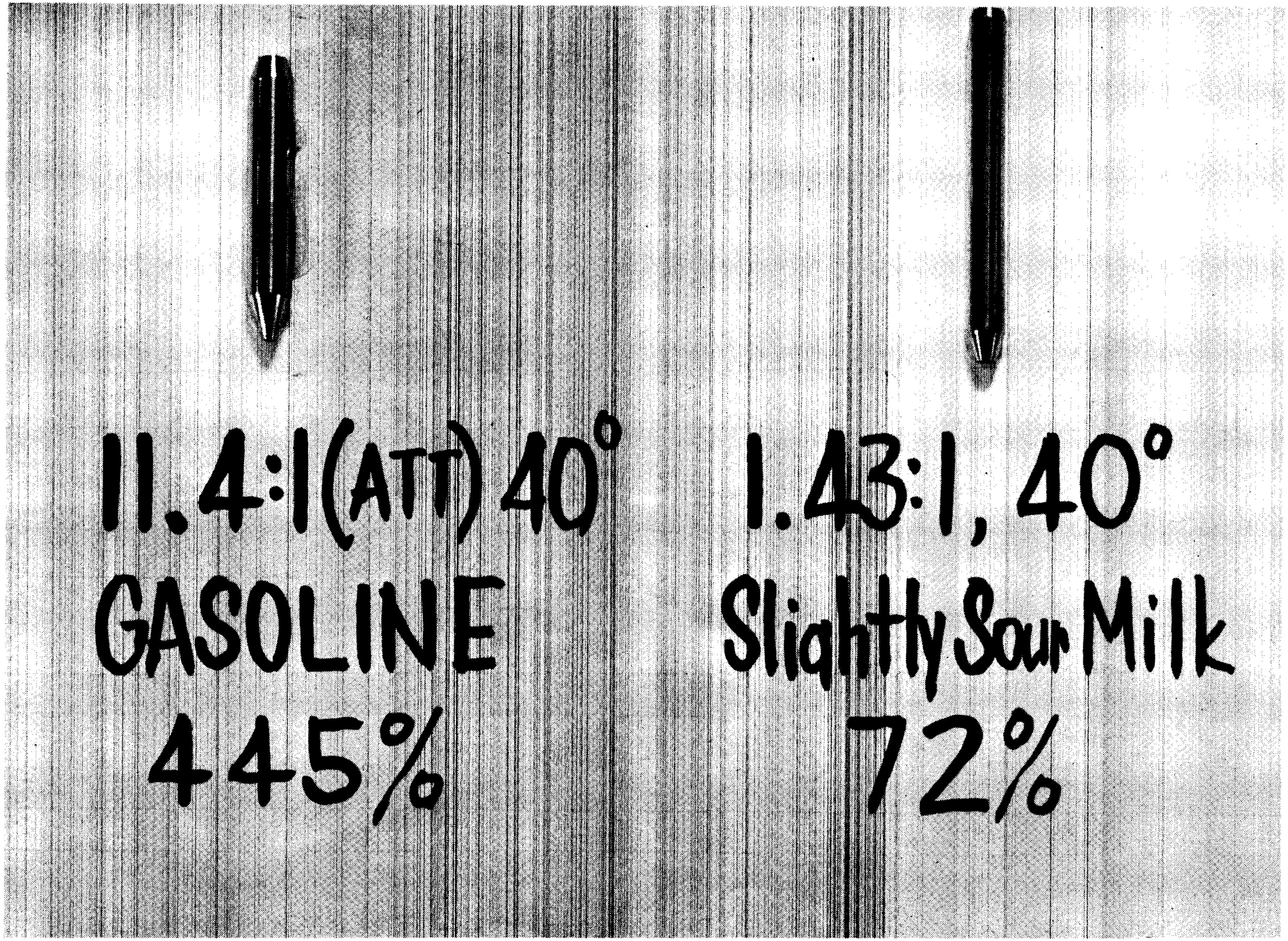

11.4:1(ATT) 40°
GASOLINE
445%
1.43:1, 40°
Slightly Sour Milk
72%

Figure 4 -- Fluid-to-fluid extruded AISI 1015-1020 steel. Reduction ratio, lubricant, and relative extrusion pressure are shown.

"Propriet" means "proprietary";
"T. Oil" means "transformer oil"; and
"Kero" means "Kerosene".

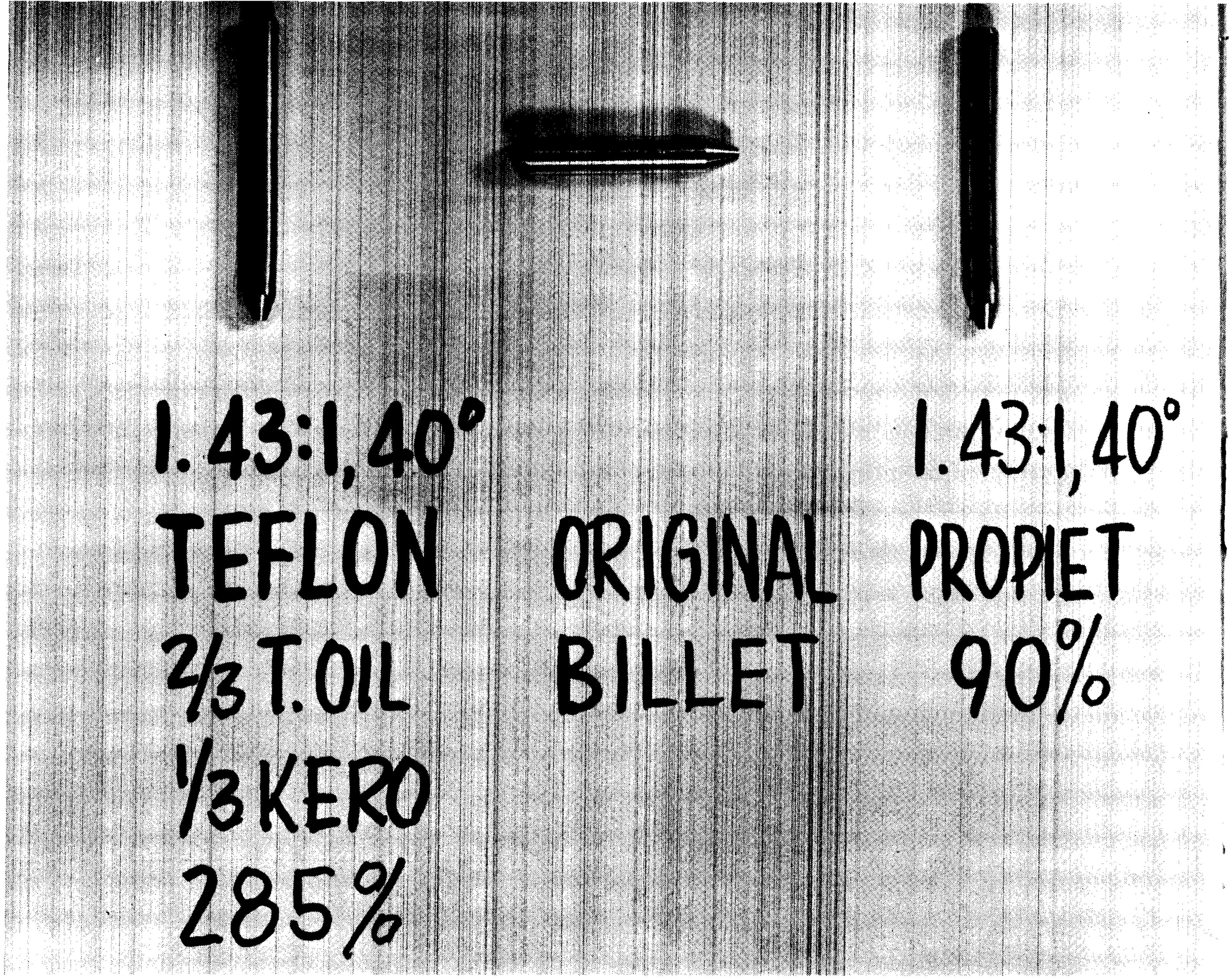

1.43:1, 40°
TEFLON
2/3 T.OIL
1/3 KERO
285%
ORIGINAL
BILLET
1.43:1, 40°
PROPIET
90%

Figure 5 -- Fluid-to-fluid extruded AISI 1015-1020 steel. Reduction ratio, lubricant, and relative extrusion pressure are shown.

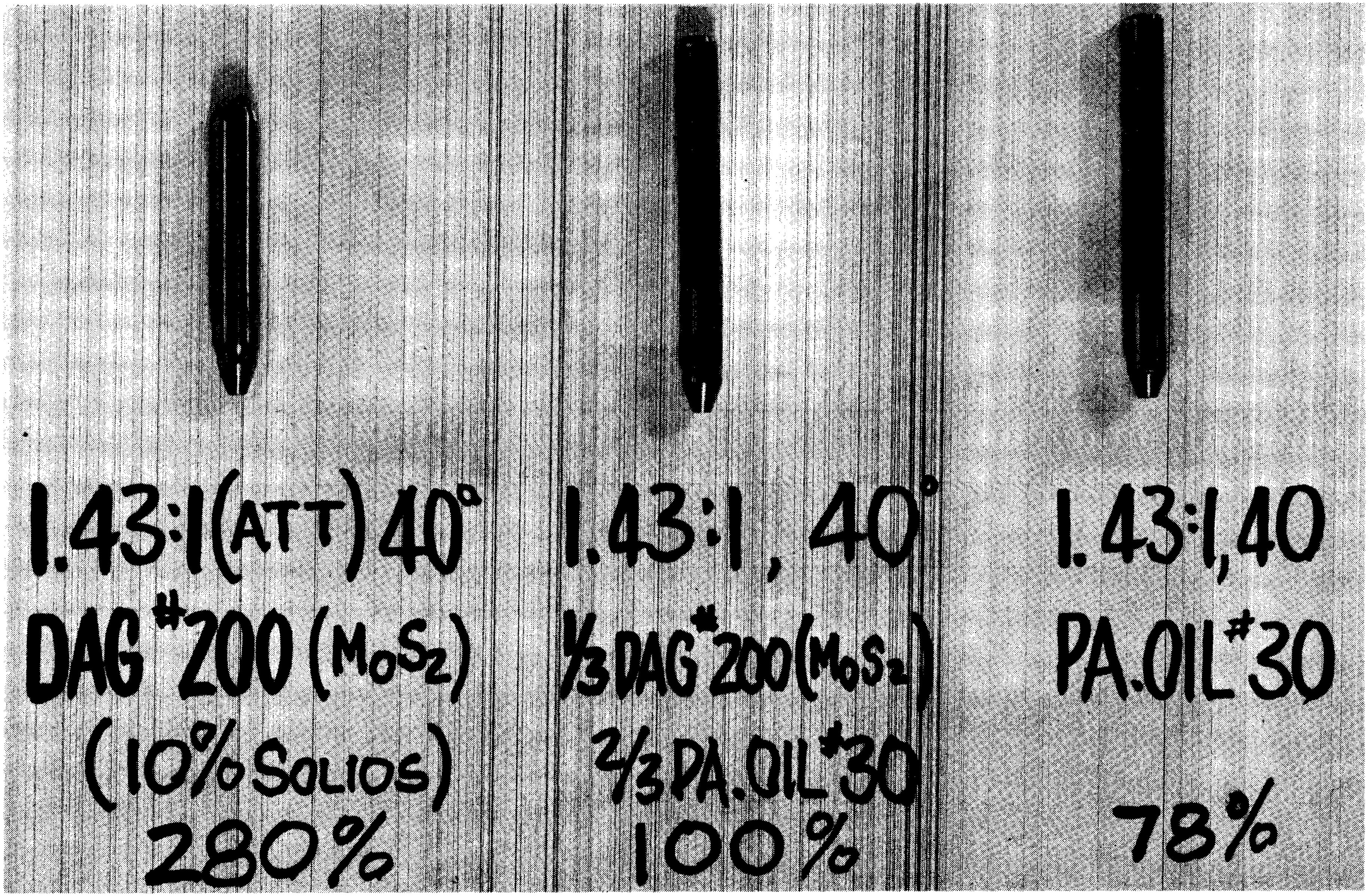
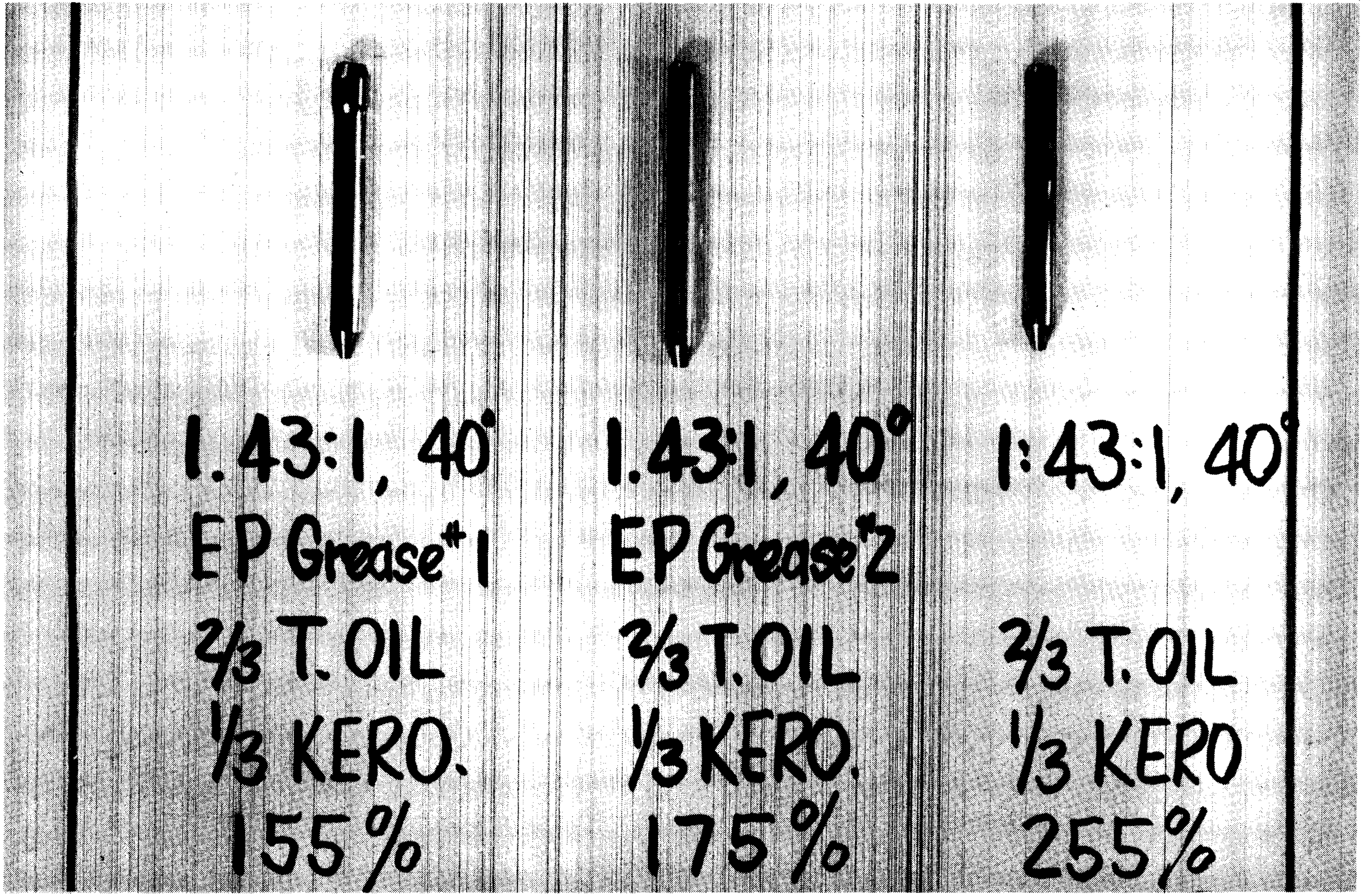

1.43:1 (ATT) 40°
DAG #200 (MoS2)
(10% SOLIDS)
280%
1.43:1, 40°
1/3 DAG #200 (MoS2)
2/3 PA. OIL #30
100%
1.43:1, 40
PA. OIL #30
78%

Figure 6 -- Fluid-to-fluid extruded AISI 1015-1020 steel. Reduction ratio, lubricant, and relative extrusion pressure are shown.

"T. Oil" means "transformer oil"; and
"Kero" means "Kerosene.



1.43:1, 40°
EP Grease #1
2/3 T. OIL
1/3 KERO.
155%
1.43:1, 40°
EP Grease #2
2/3 T. OIL
1/3 KERO.
175%
1:43:1, 40°
2/3 T. OIL
1/3 KERO
255%

Figure 7 -- Fluid-to-fluid extruded AISI 1015-1020 steel. Reduction ratio, lubricatn, and relative extrusion pressure are shown.

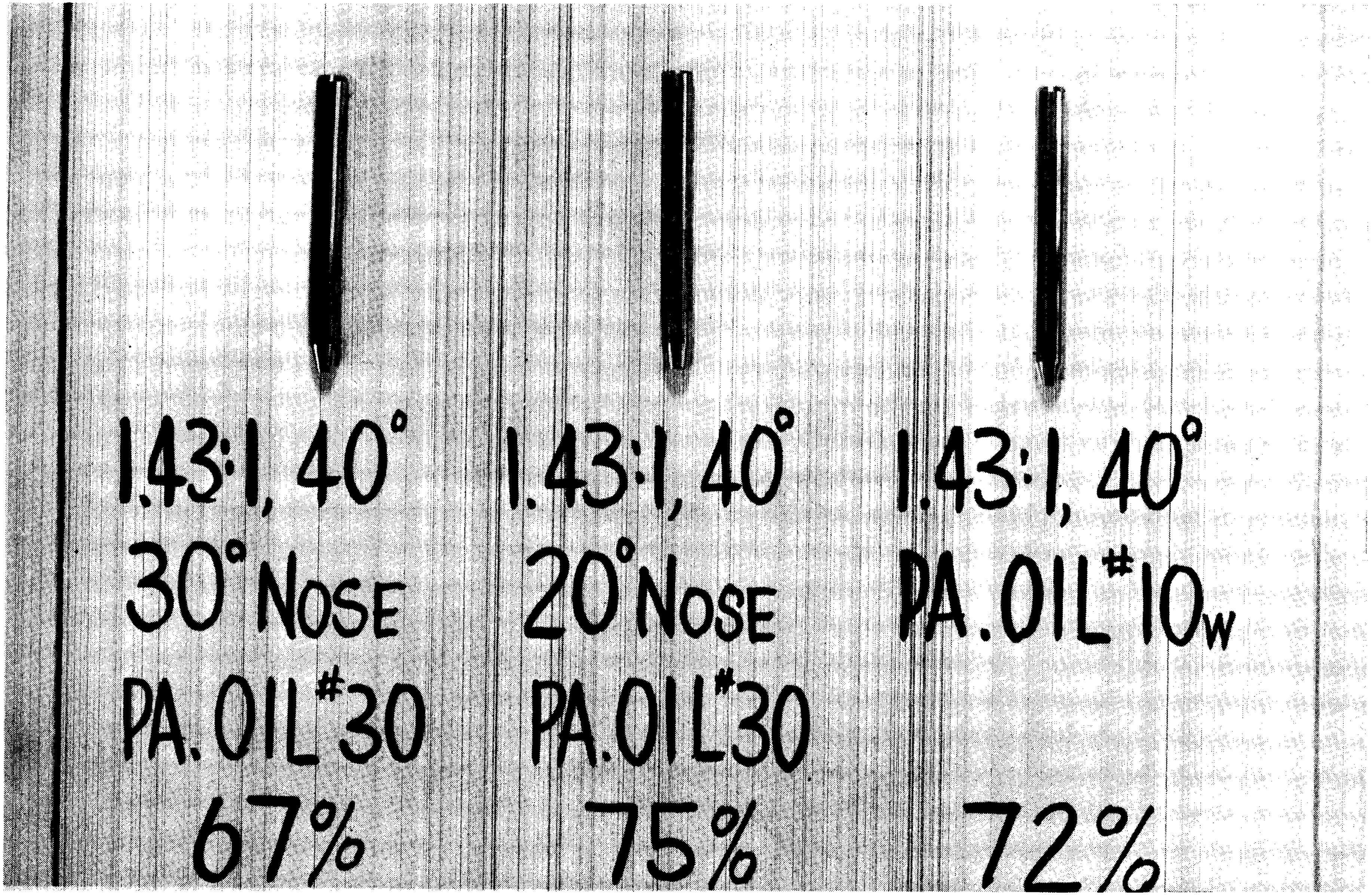

1.43:1, 40°
30° NOSE
PA. OIL #30
67%
1.43:1, 40°
20° NOSE
PA. OIL #30
75%
1.43:1, 40°
PA. OIL #10W
72%

Figure 8 -- Fluid-to-fluid extruded AISI 1015-1020 steel. Reduction ratio, lubricant, and relative extrusion pressure as shown.

"F.P." means "freezing point".

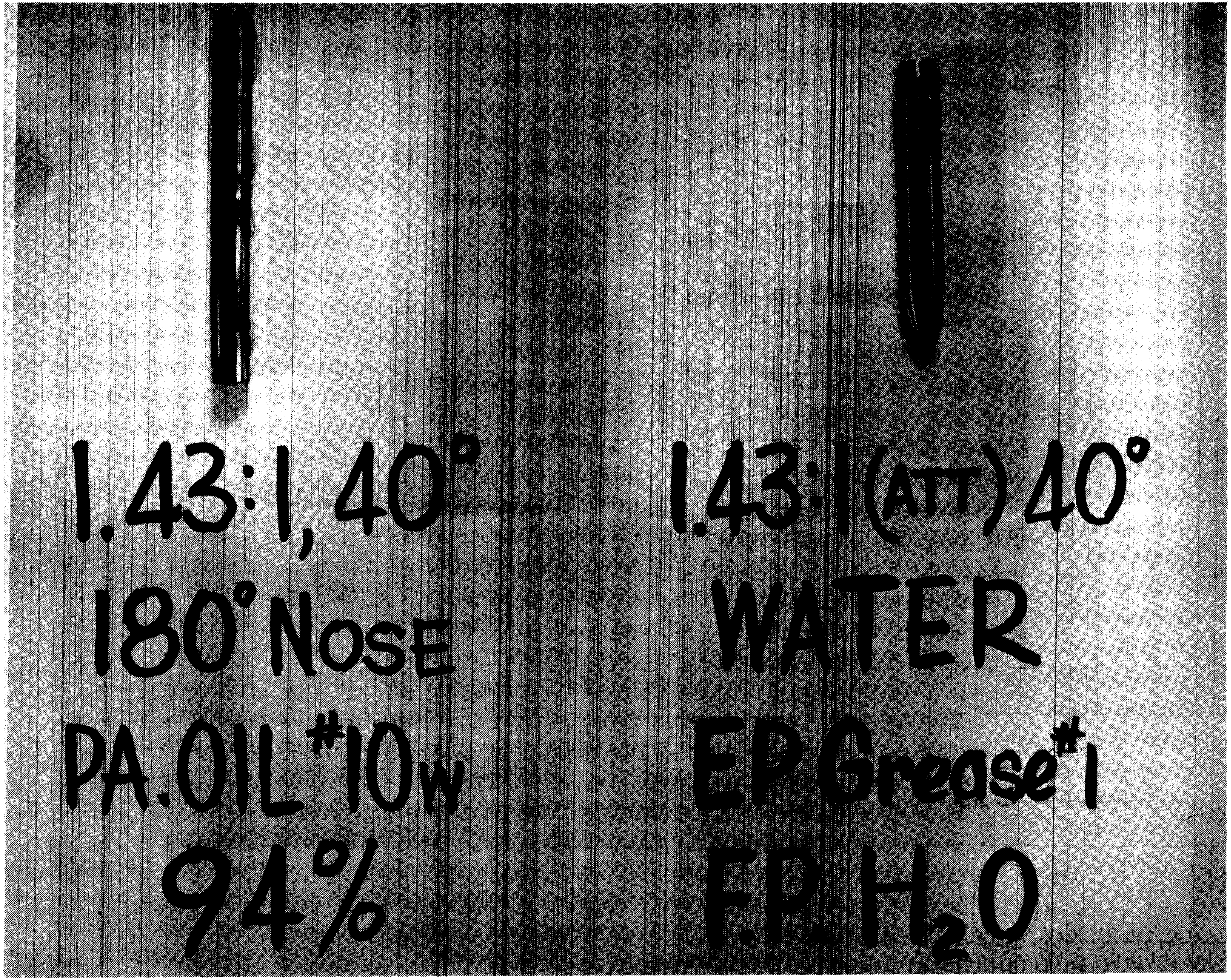

1.43:1, 40°
180° NOSE
PA. OIL #10W
94%
1.43:1 (ATT) 40°
WATER
EP Grease #1
F.P. H2O

Table II

Some Effects of Lubricants on
Fluid-To-Fluid Extrusion of Low Carbon Steel

Lubricant	Resulting Surface Finish	Relative Pressure, %	Comment
-----	Good to Fair	----	Original billet
Dag #200(MoS_2) (10% solids)	----	280	No extrusion; fluid solidified
1/3 Dag#200(MoS_2) (10% solids) plus 2/3 Pa. #30 oil	Excel. to Good	100	
Pa. #30 oil	Excel. to Very Good	78	
Pa. #30 oil	Very Good to Good	67	30° Nose on billet
Pa. #30 oil	Good to Fair	75	20° Nose on billet
Pa. #10W oil	Excel. to Fair	72	
Pa. #10W oil	Excel. to Fair	94	180°Nose on billet
Water + EP grease #1	----	Freezing pt. of Water	No extrusion: fluid solidified
Slightly sour milk	Excellent	72	
2/3 transformer oil + 1/3 kerosene	Excel. to Very Good	255	Used much in USSR as a std. lubricant
2/3 transformer oil + 1/3 kerosene	Good to Fair	285	Teflon on billet
Proprietary + EP Grease #1	Rough	155	
Proprietary + EP Grease #2	Rough & Wavy	175	
Proprietary	Excellent	90	

In table II, EP Grease #1 is a Soda-base grease whereas EP Grease #2 is a Lithium-base grease. Pennsylvania oil was selected instead of Oklahoma or California oils because of lower viscosity index. The slightly sour milk that was used contains a weak acid, a fatty dispersant for lubricity, dissolved solids for anti-galling action, and unknown biological entities. The latter gave the best or next to the best surface finish of all materials tried, and nearly the lowest extrusion pressure.

Increased Strength and Ductility From Pressure Processing

The theory, supported to a good extent by experiments, presented earlier in this report indicated that microcracks could be self-healed by a combination of pressure and shear displacement, similar to cold welding. The logical extension of this thought is that strength and ductility can be increased in this way. More specifically, one would expect behavior as in table III (also see figure 9).

Table III

Comparative Behavior of Metalworking With And Without Superposed Pressure

Region	Description	Behavior
I	Cold working has been done, but not very much.	Microcracks have not formed at all or to any large extent; metalworking with and without superposed pressure should yield identical rising strengths and decreasing ductilities
II	Enough cold working has been done that physical properties are not rising as rapidly as in region I in ordinary metalworking.	UTS and ductility of material worked under pressure should exceed the same properties of material worked the same amounts without pressure; material worked by either process should show higher strength and lower ductility than in region I.

ERRATA

There is no page 25 in this report.

Table III (cont)

Region	Description	Behavior
III	So much cold working has occurred that both strength and ductility have dropped compared to region II, for ordinary metalworking	Material worked under pressure may still be manifesting increase in strength, and a lesser drop in ductility than material worked under no pressure.
IV	Additional cold work has made material dead-brittle, with very little strength, by ordinary metalworking.	Material worked under pressure shows strength high but dropping off. Ductility is dropping.

Obviously, the higher the pressure the greater the amount of cold working before deterioration occurs (for "normal" materials; "anomalous" materials are discussed later).

At this point one seeks experimental verification of the extension to previous theory, as given in table III. The verification can come from any metalworking process so long as it possesses comparative data with and without superposed pressure. The general behavior expected is shown in figure 9.

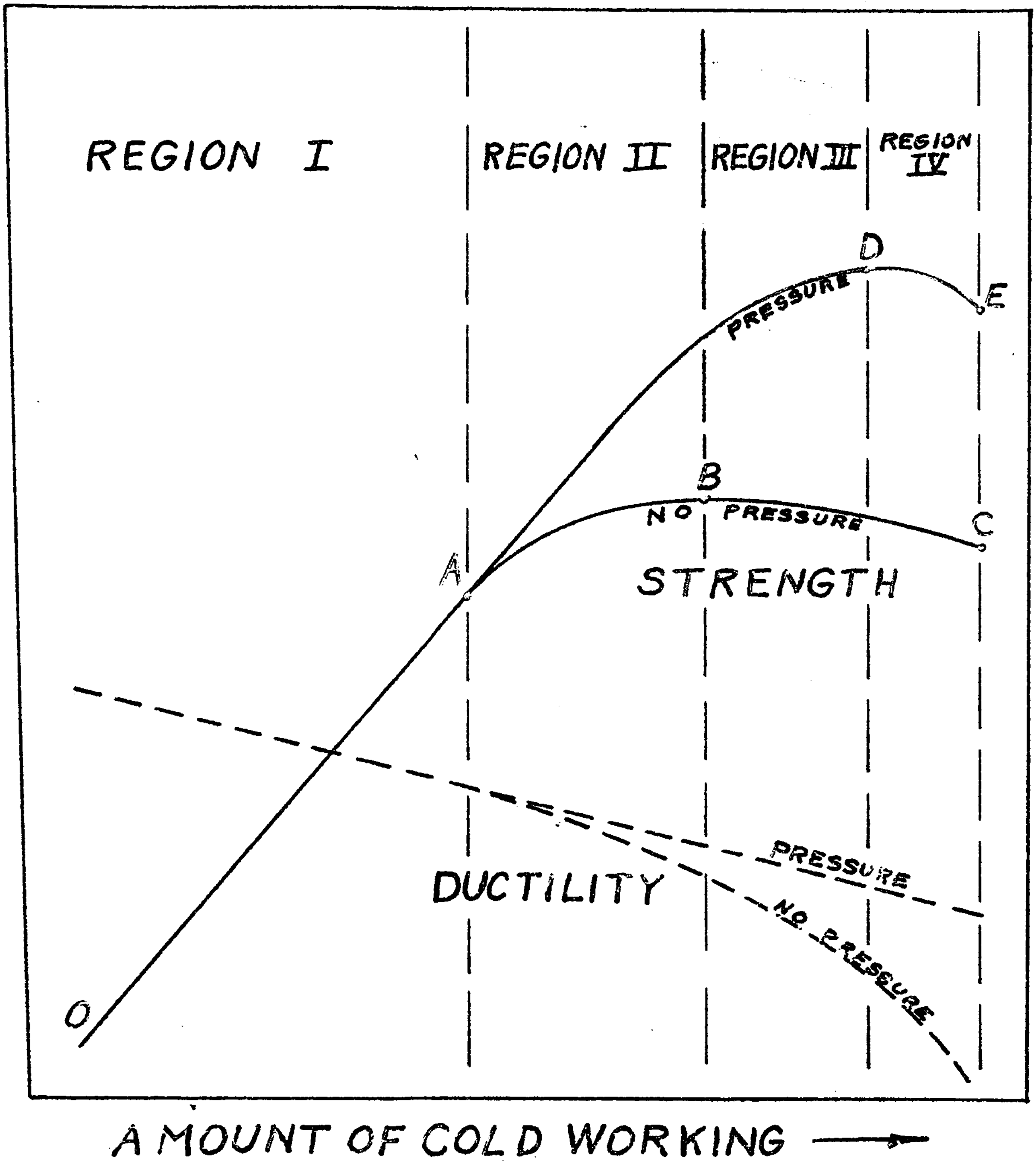


Figure 9 -- Behavior of a material cold-worked with and without pressure, schematic.

Point A represents the maximum amount of cold working without difference in properties under pressure or not. Points B and D represent the maximum strengths achievable by working without and with pressure respectively. Points C and E represent the strengths at zero ductility, without and with pressure.

Bridgman (reference 2) drew carbon-steel wire under no pressure, and under 170,000 p.s.i. He found that there was indeed an identical region OA (figure 9) for both processes at small amounts of working. Point B was not determined, but point C (corresponding to zero ductility for wire drawn under no pressure) was located at a value of $\ln$ (original area/final area) equal to 1.9, and UTS equal to 430,000 p.s.i. for 0.026-inch wire. Point D lay at 580,000 p.s.i. UTS for some diameter of wire greater than 0.026 inch. Point E was located at $\ln$ (original area/final area) equal to 1.9, above point C, with UTS of 530,000 p.s.i. Ductility below point E was 29% RA. It can be seen that figure 9 does describe this situation.

Another example of a metalworking process under pressure is fluid-to-fluid extrusion at different pressures for different amounts of cold working of aluminum (reference 15). Here one finds that for 56.2% reduction, strength and ductility are unchanged in the range from atmospheric pressure to about 105,000 p.s.i. pressure. This corresponds to points on OA of figure 9. For 75.4% reduction, ductility rises from nearly 91% RA in tensile tests on specimens fluid extruded into atmospheric pressure to nearly 94% RA for specimens fluid-to-fluid extruded into 105,000 p.s.i. pressure. This tend is definitely established by seven data points in the pressure range given. Similarly, for 75.4% reduction yield strength rose from 20,250 p.s.i. to 23,400 p.s.i. as receiver pressure rose from atmospheric to 105,000 p.s.i. (10 data points). These data establish that AB and AD (or parts of them) exist as in figure 9.

The key to this behavior lay in tensile data under pressure which indicated that RA increased with pressure, in general. Numerous examples of materials with this property are given in reference 15. These materials are termed "normal".

Some materials increase less in ductility than do others (18-8 steel compared to 12-.5 steel, reference 15). These materials, while "low normal" should yield lesser benefits by working in a pressure environment.

Finally, some materials rise in ductility with pressure up to a certain pressure, and then "saturate", that is, further increase in pressure produces little or no increase in ductility. An example is gamma brass and some steels (reference 15). These steels are termed "anomalous". For these materials there is a finite pressure cold-working above which yields no more benefit to strength and ductility. Examples of these "anomalous" materials exist in literature.

The conclusion can be reached that proper metalworking under pressure can lead to improved strength and ductility compared to metalworking without pressure, in general. Further, mechanical properties of metals worked under pressure derive more benefit as the pressure is increased, for "normal" materials. For "anomalous" materials, there is a limiting value of environmental pressure above which no further benefit to mechanical properties is derived.

COMMENTS

The steel-lubrication program has contributed knowledge on good lubricants for fluid-to-fluid extrusion, for later use in this program.

The Mar-Aging steel results demonstrate that high yield point is no impediment to fluid-to-fluid extrusion.

The tensile tests under pressure will continue, as will fluid-to-fluid extrusion of the several materials under study.

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